sustainability

MDPI

Review

Toward Rigorous Telecoupling Causal Attribution: A Systematic Review and Typology

Andrew K. Carlson [1,*], Julie G. Zaehringer [2], Rachael D. Garrett [3], Ramon Felipe Bicudo Silva [4], Paul R. Furumo [5], Andrea N Raya Rey [6,7], Aurora Torres [8,9], Min Gon Chung [1], Yingjie Li [1] and Jianguo Liu [1]

1 Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, 115 Manly Miles Building, 1405 S. Harrison Road, East Lansing, MI 48824, USA; Chungm13@msu.edu (M.G.C.); liyj@msu.edu (Y.L.); liuji@msu.edu (J.L.)
2 Centre for Development and Environment, University of Bern, Mittelstrasse 43, 3012 Bern, Switzerland; julie.zaehringer@cde.unibe.ch
3 Department of Earth and Environment and Global Development Policy Center, Boston University, 685 Commonwealth Avenue, Boston, MA 02215, USA; rgarr@bu.edu
4 Center for Environmental Research and Studies, State University of Campinas, Campinas, SP 13083-867, Brazil; ramonbicudo@gmail.com
5 Department of Environmental Sciences, University of Puerto Rico-Río Piedras, San Juan 00931, Puerto Rico; pfurumo@gmail.com
6 Centro Austral de Investigaciones Científicas (CADIC), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), B. Houssay 200, Ushuaia V9410BFD, Tierra del Fuego, Argentina; arayarey@cadic-conicet.gob.ar
7 Instituto de Ciencias Polares, Ambiente y Recursos Naturales, Universidad Nacional de Tierra del Fuego, Hipólito Yrigoyen 879, Ushuaia 9410, Tierra del Fuego, Argentina
8 German Centre for Integrative Biodiversity Research (iDiv), Deutscher Platz 5e, 04103 Leipzig, Germany; aurora.torres@idiv.de
9 Institute of Biology, Martin Luther University Halle-Wittenberg, 06108 Halle (Saale), Germany
* Correspondence: andrewcarlson422@gmail.com; Tel.: +651-280-7013

Received: 12 October 2018; Accepted: 23 November 2018; Published: 27 November 2018

Abstract: Telecoupled flows of people, organisms, goods, information, and energy are expanding across the globe. Causes are integral components of the telecoupling framework, yet the rigor with which they have been identified and evaluated to date is unknown. We address this knowledge gap by systematically reviewing causal attribution in the telecoupling literature (n = 89 studies) and developing a standardized causal terminology and typology for consistent use in telecoupling research. Causes are defined based on six criteria: sector (e.g., environmental, economic), system of origin (i.e., sending, receiving, spillover), agent, distance, response time (i.e., time lapse between cause and effect), and direction (i.e., producing positive or negative effects). Using case studies from the telecoupling literature, we demonstrate the need to enhance the rigor of telecoupling causal attribution by combining qualitative and quantitative methods via process-tracing, counterfactual analysis, and related approaches. Rigorous qualitative-quantitative causal attribution is critical for accurately assessing the social-ecological causes and consequences of telecouplings and thereby identifying leverage points for informed management and governance of telecoupled systems.

Keywords: telecoupling; causality; cause; effect; coupled human and natural systems

1. Introduction

The scope and intensity of human-environment interactions have increased dramatically since the Industrial Revolution. For example, human appropriation of net primary productivity doubled between 1910 and 2005, reaching 25% of all biomass generated by terrestrial vegetation [1]. As on land, "distant water" fishing in oceans—commercial fishing by nations in areas distant from their shores—expanded in the mid-twentieth century and continues today in all corners of the globe [2]. Scientists now recognize the existence of coupled human and natural systems (CHANS) wherein people interact with natural components [3]. Although conceptually uncomplicated, CHANS are highly complex, involving reciprocal human-environment interactions characterized by intricate feedback loops, nonlinearity, thresholds, and legacy effects. In a globalized world wherein CHANS are increasingly discernible, their complexity is hardly a reason to halt CHANS research, management, and governance. Indeed, much of CHANS research seeks to uncover and quantify the magnitude and direction of processes linking human and natural systems so they can be sustainably managed and governed [3–5].

As an example, the telecoupling framework [3] is a systematic tool for studying complex ecological, economic, political, social, and cultural interactions among CHANS over distances (i.e., telecouplings). By facilitating simultaneous assessment of reciprocal socioeconomic and environmental interactions among distant CHANS, the telecoupling framework advances related paradigms, such as globalization (i.e., socioeconomic interactions between human systems) and teleconnections (i.e., environmental interactions between natural systems) [3]. The telecoupling framework is composed of flows, systems (e.g., nations, nature reserves, marine protected areas), agents, causes, and effects. Flows are movements of entities (e.g., money, people, materials, information) between sending and receiving systems. Flows are facilitated by agents (individuals or groups of humans/animals), driven by causes (socioeconomic/environmental reasons), and characterized by effects (socioeconomic/environmental impacts) [6,7]. Systems encompass different sets of agents and the flows arising from those agents. Systems interact with each other and boundaries can be adjusted to incorporate metacouplings (i.e., human-nature interactions within and between adjacent and distant places) [8]. To date, the telecoupling framework has been applied to numerous topics in sustainability science, including international trade [9,10], land-use change [11,12], fisheries [13,14], wildlife [15], water transfer [16,17], urbanization [18], and species invasion [19].

A critical step in applying the telecoupling framework is identifying causes of telecoupled interactions among CHANS. Generally speaking, a cause is something that explains an effect or effects. Both causes and their effects can be events, variables, or facts [20]. Lazarfield [21] stated that a causal relationship between A (a cause) and B (an effect) requires a temporal association (i.e., A occurs before B) and an empirical correlation between A and B that cannot be explained away by another variable that causes both A and B. Yet, causality is more than causes and effects; it involves intricate processes that connect causes to effects in different ways depending on context [22]. In telecoupled systems, causes often work in combination, making them insufficient, necessary, unnecessary, or sufficient (INUS) causes, which are insufficient but necessary parts of a combination of causes, which is itself unnecessary but sufficient for the effect(s) [20,23]. The INUS cause literature distinguishes between equifinality (i.e., same effect(s) produced by different INUS combinations) and multifinality (i.e., different effects(s) produced by the same INUS combinations) [24]. In the scientific disciplines in which the telecoupling framework has been applied, authors routinely invoke equifinality to explain effects. For instance, in land system science, forest transitions (i.e., the return of forest cover in areas previously deforested) [25] have been explained via distinct INUS combinations, including: increased imports; abandonment of marginal lands; reforestation policies to cope with forest scarcity, water loss, and soil erosion; and adoption of eco-friendly practices such as environmental certification protocols [26–28]. An informative way to address the complex, combinatorial nature of causality in the telecoupling framework is to first distinguish between causal effects and causal mechanisms. A causal effect is the change in a response variable brought about by change in an explanatory variable [20]. Despite its importance for determining telecoupling causality, evaluating causal effects is insufficient for robust causal analysis of telecouplings because it does not answer "How?" This is the realm of causal mechanisms: the processes whereby an explanatory variable produces its effects [20].

In telecoupling research, rigorous causal attribution—combining qualitative and quantitative methods to triangulate, broaden, and deepen evidence for causes and causal mechanisms and effects—is important because it enables researchers to accurately characterize the social-ecological complexity of telecouplings and thereby develop informed strategies for the management of telecoupled systems [29]. "Mixed" (qualitative-quantitative) methods allow researchers to validate study results (triangulation), investigate related but distinct social-ecological phenomena (complementarity), develop findings derived from one method using those from another (development), provide new perspectives (e.g., similarities, paradoxes) beyond those generated by single methods (initiation), and ultimately expand the scope of social-ecological analysis (expansion) [30]. Rigorous causal attribution is far from straightforward, and there have been many different terms used to describe causal processes (e.g., cause vs. driver vs. determinant, causal effect vs. causal mechanism, proximate vs. underlying cause) [20]. It remains unclear if and how telecoupling researchers have addressed these and related concepts extending beyond simple "cause" and "effect." In addition, specific research designs (e.g., case studies, models, experiments) and methods (e.g., process-tracing, statistical analysis) used to identify causes have not been thoroughly assessed regarding their applicability for telecoupling research, so effective techniques for ascertaining telecoupling causes are largely unknown.

Answers to these and related questions are crucial for maximizing the utility and reliability of the telecoupling framework and ensuring that decisions regarding the management and governance of telecoupled systems reflect accurate causal analyses. Describing and quantifying the relative magnitude of different causes and the mechanisms through which they generate effects in telecoupled systems is essential for identifying leverage points (e.g., key people and organizations) for improved management and governance of telecoupled systems. This is particularly important at a time when the telecoupling framework is poised to help policy makers evaluate the effectiveness of governance initiatives for achieving the United Nations Sustainable Development Goals (SDGs) [31], the Aichi Targets [32], the Paris Agreements [33], and other global initiatives [34]. Hence, the goal of this paper is to develop a structured, standardized approach for causal attribution in telecoupling research. Our objectives are to: (1) describe best practices for causal attribution in telecoupling research; (2) assess the nature of causality assessment in prior telecoupling studies in terms of qualitative and quantitative methods; and (3) generate a standardized causal terminology and typology for use in the research, management, and governance of telecoupled systems.

2. What Are Best Practices for Assessing Causality Using the Telecoupling Framework?

Best practices for assessing causality in telecoupling research start with developing rigorous qualitative and quantitative linkages between known information on telecoupled systems and research goals and analyses. That is, researchers should use existing information about telecouplings (e.g., descriptive, correlational, quasi-experimental) to establish qualitative and quantitative pathways for connecting telecoupled systems with the purpose(s) of a particular study. Potential research designs for assessing causal influences in telecoupled systems include case studies, comparative case studies, experiments, and modeling, while research approaches include process-tracing and statistical analyses such as pair-wise comparisons, multivariate econometrics, and Boolean algebra. The relative commonality of complex causal relationships in telecoupled systems highlights an important distinction between causality in the experimental sciences versus the observational and historical sciences (e.g., history, sociology and—more recently—land system science and social-ecological systems) [20]. Experimental sciences evaluate causality using variables that can be readily replicated, controlled, and assessed in terms of their agreement with general laws. Experimental approaches are extremely rare in telecoupling research due to their scope and complexity, yet many statistical approaches exploit natural variations in conditions, resulting in natural or quasi-experimental designs [35]. In the absence of general laws, the observational sciences focus on case-specific occurrences of observed phenomena that generally are not replicable or controllable; causality is inferred, not proven [36–38]. Hence, in social-ecological systems and other observational disciplines, causal effects and causal mechanisms are often context-dependent, making it all the more important to understand causality in the telecoupling framework and develop systematic approaches for accurate, reliable causal attribution that is qualitatively and quantitatively rigorous.

Two types of inference are typically pursued when establishing causal claims in telecoupled systems: (1) predictive inference, and (2) causal inference [35]. Predictive approaches aim to elucidate causal relationships by evaluating associations between explanatory and response variables. However, predictive relationships between variables do not necessarily imply a causal relationship, as other variables (confounders) can influence explanatory and response variables [39]. Causal inference, on the other hand, is concerned with ruling out rival explanations for the estimated relationship between two variables [40]. This is more challenging because confounding factors, both observable and unobservable, must be accounted for (Figure 1). To distinguish between predictive versus causal inference when using multivariate statistical approaches, it is necessary to start with a strong underlying theoretical framework (i.e., qualitative knowledge) and associated assumptions about the causal relationships underlying the model structure [35]. Thus, model fit should not be prioritized over model structure, especially because fit can be a consequence of positive feedback loops (reverse causality) between the dependent and independent variables. Ideally, qualitative knowledge about telecoupled systems will provide insights for conducting quantitative analyses, particularly those that test causality between a variable of interest and a response variable while avoiding interference (collinearity) between potential explanatory variables, as it could lead to inaccurate estimates for each individual predictor. However, this is often difficult or impossible in telecoupling research given the interconnectedness of most systems [35].

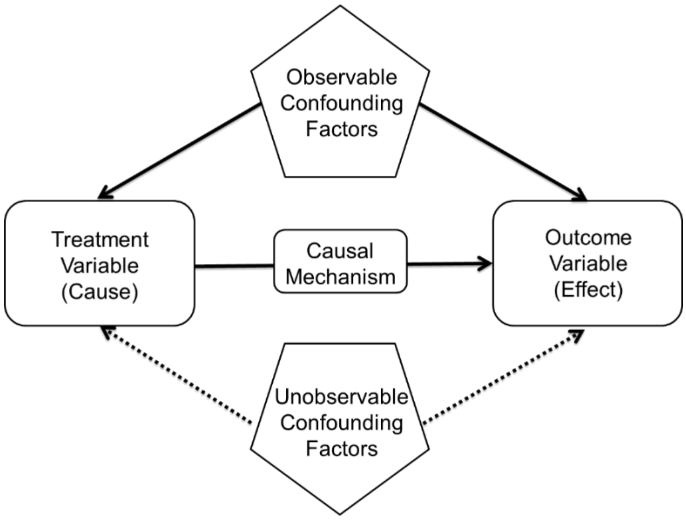

Figure 1. Graphical basis for establishing causal relationships and the confounding factors that obfuscate causality. Treatment variables (causes) exert effects on response (outcome) variables via causal mechanisms that can be influenced by observable and unobservable confounding factors (distinguished by solid and dashed lines). Figure adapted from [35].

Counterfactual analysis, a form of scenario analysis, is often a critical step in assessing causality. It enables cause identification by reversing causal thinking: if A is a necessary cause of B, B will not occur without A, all else being equal [20]. Researchers can use this line of reasoning to assess relationships between effects and hypothesized causes in telecoupled systems. For example, to test whether trade causes land-use change, counterfactual analysis would involve combining qualitative and quantitative information to evaluate land use in the absence and presence of trade and thereby determine if trade indeed causes land-use change, all else being equal. Likewise, to determine whether a policy or conservation program causes improvement in human well-being, researchers would evaluate human well-being in the absence of the policy/program to determine if it is the cause of increased well-being. In combination with qualitative description and tools such as statistical matching, synthetic control methods, and instrumental variables, counterfactual analysis can help researchers to explicitly understand the limitations of observational data, identify effects of treatment variables on response variables [41], and ultimately evaluate proximate (i.e., direct) and underlying (i.e., indirect, root) cause(s) of telecouplings in a rigorous manner that combines qualitative and quantitative knowledge [20,42,43]. However, counterfactual analysis is not always applicable as it can be difficult, if not impractical, to locate study systems and sufficiently large sample sizes that differ in only a single variable of interest, all else being equal. The potential array of unobservable confounders is particularly challenging in telecoupled systems and reinforces the need for an in-depth qualitative understanding of study systems prior to quantitative causal attribution.

The most appropriate method for establishing counterfactuals and identifying causal effects depends on the type of data available. Because telecoupling research is based on observational data in most cases, evaluations are commonly conducted retroactively, or *ex post*. The datasets utilized in telecoupling studies are often cross-sectional (e.g., socioeconomic household data, national trade data), time-series (e.g., national forest cover), or a combination of both. As randomized experiments are difficult to establish in this setting, matching is often performed to pair treatment and control samples for comparison. Matching requires that the characteristics of both groups have sufficient overlap [39]. Pair-matched, case-control methods can be used to compare samples along a gradient of a particular attribute when confounding factors are well-documented and have been used with success in evaluating the effectiveness of eco-certification programs (e.g., coffee [44]). Statistical methods such as propensity score matching is useful when sufficient ancillary information is available. These methods help improve the balance of treatment and control groups and neutralize the effect of confounding factors but are limited by small sample sizes. After groups are paired, treatment effects are estimated, which often relies on regression models. Cross-sectional data can have limited usefulness for establishing causal effects because of the difficulty of controlling for all the factors influencing effects [39]. However, combinations of time-series and cross-sectional data, also known as panel data, improve the robustness of causal inference efforts if they include baseline data before an intervention [39,45]. Panel data allow individuals to serve as their own controls, and reliable treatment effects can be attained using regression and fixed effects by way of difference-in-difference or before-after-control-impact approaches [41,45,46]. The ability of panel data to eliminate the confounding effects of fixed unobservable attributes and time-variant observable attributes [35] makes these data preferable for telecoupling research, despite the need for large and varied datasets.

Case study and comparative case-study approaches are important qualitative methods for causal inference, particularly when such approaches incorporate a time dimension. Individual case studies can be thoroughly deconstructed and compared to other case studies using process-tracing, a method for assessing causal mechanisms using detailed empirical analysis of how causal processes unfold. Process-tracing involves four phases: (1) identify the steps linking explanatory variables to response variables; (2) assess the internal consistency (logic) and external consistency (empirical evidence) of each step; (3) identify and test implications of each step, including those extending beyond the main cause-effect linkage; and (4) explore and refute counterhypotheses (i.e., competing explanations) to the main hypothesis [20,47]. Telecoupling researchers can use process-tracing to understand how proximate and underlying causes interact to produce effects and thereby ensure the accuracy of causal mechanisms for telecouplings.

We propose that telecoupling causal attribution should emphasize combining methods that are qualitative (e.g., case studies) and quantitative (e.g., structural equation modeling, two stage least squares analysis) to evaluate both the proximate and underlying causes of a given effect. For instance, explaining land-use and land cover change should involve describing spatiotemporal patterns in landscape condition and using qualitative and quantitative methods to examine the proximate and underlying causes of those patterns [48]. Integrative qualitative-quantitative methods are important in telecoupling research because they provide multiple lines of evidence for establishing telecoupling causality while accounting for the inherent complexity of telecoupled systems. For example, often an independent variable X (e.g., agricultural policy in a distant nation) secondarily changes a dependent variable Y (e.g., domestic land cover) by modifying intermediate variables (e.g., trade flows) in telecoupled systems that are best understood using multiple qualitative and quantitative techniques. In these cases, qualitative-quantitative methods are better suited for accurate causal attribution than either qualitative or quantitative methods alone. Well-established in fields such as psychology, systems engineering, and medicine, Root-Cause Analysis (RCA) is particularly well-suited for telecoupling research because it integrates social-ecological and spatiotemporal information to systematically explain how underlying causes lead to proximate causes and effects [49,50]. However, RCA is one of many rigorous qualitative-quantitative methods for assessing proximate and underlying telecoupling causes that will help researchers decipher causal mechanisms, operationalize the telecoupling framework, and advance management and governance of telecoupled systems.

3. Causality Assessment in the Telecoupling Literature

A systematic review of telecoupling research was performed using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) procedure described in [51] (Figure S1). Telecoupling-related peer-reviewed publications (i.e., journal articles, book chapters) were located with an inclusive search criterion relevant for a telecoupling study (i.e., telecoupling OR tele-coupling OR telecoupled OR tele-coupled, language = English) in Web of Science (www.webofknowledge.com), which searches paper titles, abstracts, and keywords for given search terms. The same search criterion was also used in Google Scholar (www.scholar.google.com) to locate additional peer-reviewed publications. Of 96 non-duplicate publications located, seven were removed because they were published after the time frame of the review (i.e., 2011 (earliest telecoupling publication) through May 2018). Thus, 89 publications (Table S1) were located and evaluated by two separate reviewers with respect to causal claims made and methods used to assess causality via a thorough reading of the abstract, introduction, methods, results, and discussion. Overall, 20.2% of assessed papers (n = 18) did not qualify as true telecoupling papers (Figure 2), meaning they only mentioned the term but did not conduct a study of telecoupling components (i.e., flows, systems, agents, causes, effects). Another 16.9% of papers (n = 15) operationalized the telecoupling concept but did not conduct a causal analysis. The remaining 62.9% of the papers (n = 56) made descriptive (i.e., qualitative) statements regarding causal effects, causal mechanisms, or both (Figure 2). More than half of these papers made use of available secondary data as opposed to original data. Only two of these papers [52,53] included rigorous (i.e., qualitative and quantitative) causal analysis methods (i.e., simulation modeling, network analysis, statistical matching; Figure 2) in addition to descriptive statements.

Evaluation of the specific causal analysis methods used in telecoupling papers provides insights for future telecoupling research. Of the 56 papers that used some form of causal analysis (i.e., descriptive or rigorous), 94.6% (n = 53) assessed causal effects, but only 67.9% (n = 38) investigated causal mechanisms. For both types of causal variables, more than 83.0% of papers cited previous sources to corroborate their causal statements (Tables 1 and 2). For the assessment of causal effects, 47.2% of papers (n = 25) used case study analysis, 20.8% (n = 11) analyzed time series data, and 15.1% (n = 8) compared case studies (Table 1). Simulation models, panel regression, natural experiments, and statistical matching were each used in less than four percent of papers. For the evaluation of causal mechanisms, case study analysis (42.1%, n = 16) and case study comparison (15.8%, n = 6) were the most commonly used methods, other than citation of previous studies (89.5%; Table 2). Some papers also used process-tracing (10.5%, n = 4) and abductive causal eventism (7.9%, n = 3), which involves working backward in time via eliminative inference from effects to causes to explain interrelated social and/or biophysical events [20].

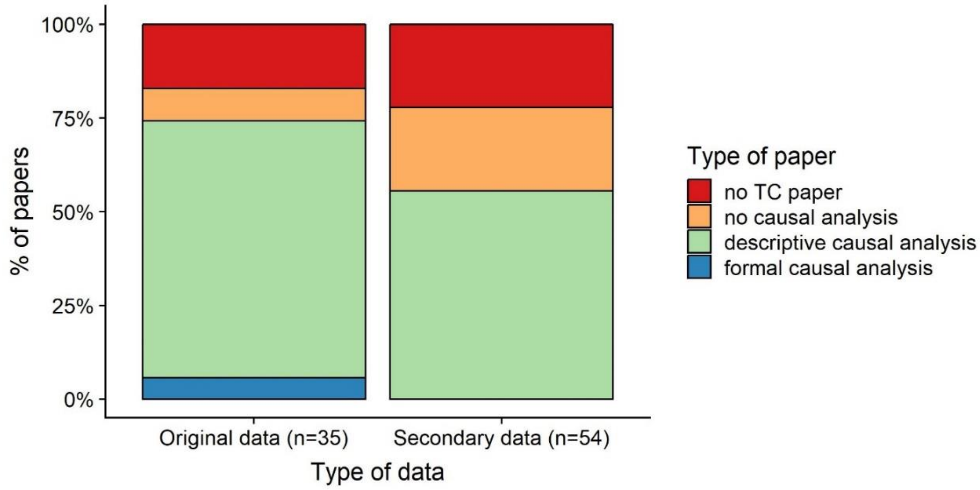

Figure 2. Overview of assessed publications in terms of the type of data used and the type of causal analysis conducted (n = 89). "TC" denotes telecoupling.

Table 1. Methods used to assess causal effects in papers that conducted descriptive (i.e., qualitative) or rigorous (i.e., qualitative and quantitative) causal analyses (n = 53 of 89).

Method	**% (n = 53)**	**#**
Cited previous sources	83.1	44
Case study analysis	47.2	25
Time series analysis	20.8	11
Other methods	18.9	10
Case study comparison	15.1	8
Simulation model	3.8	2
Panel regression	1.9	1
Natural experiment	1.9	1
Statistical matching	1.9	1
[One method]	45.3	24
[Two methods]	28.3	15
[Three or more methods]	26.4	14

Notes: "Other methods," each representing a single paper, include interviews with amphipod crustacean fishers [54], focus groups with government officials associated with the East–West Economic Corridor (Vietnam-Thailand) [55], snowball sampling for interviews with soybean stakeholders [56], emergy analysis [18], multi-regional input-output analysis (MRIO) and stochastic actor-oriented modeling (SAOM) [57], change detection analysis combined with moving window analysis [58], Qualitative Comparative Analysis (QCA) [59], and spatiotemporal coupled system dynamics modeling [60].

Table 2. Methods used to assess causal mechanisms in papers that conducted descriptive (i.e., qualitative) or rigorous (i.e., qualitative and quantitative) causal analyses (n = 38 of 89).

Method	**% (n = 38)**	**#**
Cited previous sources	89.5	34
Case study analysis	42.1	16
Case study comparison	15.8	6
Process-tracing	10.5	4
Other methods	10.5	4
Abductive causal eventism	7.9	3
[One method]	2.6	1
[Two methods]	57.9	22
[Three or more methods]	39.5	15

Notes: "Other methods," each representing a single paper, include interviews with amphipod crustacean fishers [54], focus groups with government officials associated with the East–West Economic Corridor (Vietnam-Thailand) [55], snowball sampling for interviews with soybean stakeholders [56], emergy analysis [18], and network analysis [53].

Other methods for evaluating causal effects and causal mechanisms were each used in one paper (i.e., semi-structured interviews [54], focus groups [55], snowball sampling for interviews [56], emergy analysis [18], stochastic actor-oriented modeling [57], change detection analysis [58], Qualitative Comparative Analysis [59], spatiotemporal coupled system dynamics modeling [60], and network analysis [53]; Tables 1 and 2). Additional methods appropriate for causal analysis (i.e., counterfactual analysis, synthetic controls, instrumental variables, convergent cross mapping, Rubin Causal Models) [20] were not applied in any of the assessed papers. Most papers analyzed causal effects using one method (45.3%, n = 24), whereas others used two methods (28.3%, n = 15) or three or more methods (26.4%, n = 14; Table 1). Papers that assessed causal mechanisms most often used two methods (57.9%, n = 22) or three or more methods (39.5%, n = 15; Table 2).

Overall, the literature review shows that the assessment of causality in telecoupling research has been mostly descriptive to date, generally not making use of the wide range of rigorous qualitative-quantitative methods for studying causal effects and causal mechanisms. Descriptive studies are important for understanding flows linking agents in social-ecological systems, but attribution of causes and evaluation of causal mechanisms are incomplete, if not inaccurate, without combined qualitative-quantitative analysis. For instance, Easter et al. [61] stated that projected climate change and potential shifts in protein demand could decrease the distribution of trypanosomosis, a bovine disease, and thereby increase cattle production in southern and eastern Africa, but at a cost to the environment (e.g., soil degradation, reduced biodiversity). Not only was this causal linkage speculative (i.e., based on potentialities rather than retrospective analysis), it lacked rigorous causal attribution as "causes" were only identified using a qualitative, non-statistical approach involving citation of previous literature. Although rigorous causal analysis was neither the authors' goal nor was it essential for the purposes of Easter et al. [61], such analysis is necessary to advance the state of telecoupling science. In fact, Easter et al. [61] suggest future methods for rigorous casual attribution that combines qualitative and quantitative information in their study system, including multilayer networks, socioeconomic metabolism models, and agent-based models.

Likewise, Schierhorn et al. [62] argued that the breakdown of the Soviet Union in 1991 caused transformations in Russia (e.g., new agricultural policies affecting beef production and prices, bovine disease outbreaks) and internationally (e.g., appreciation of the US dollar, beef traceability standards in Brazil) that placed Brazil at the center of Russian beef imports from the mid-2000s to 2013. Although the authors provided a thoughtful description of beef telecouplings, they did not use rigorous causal analysis to determine whether, and to what degree, these transformations caused telecoupled beef flows between Russia and Brazil. Recognizing the need for rigorous causal analysis of beef telecouplings, Schierhorn et al. [62] laid a foundation for future studies to address this important research area. Many other telecoupling studies provide detailed qualitative explanations for telecouplings (e.g., Gasparri et al. [11], Friis and Nielsen [63]), but the relative importance of various causal factors often remains elusive, creating opportunities for rigorous, mixed qualitative-quantitative causal analysis in future research.

4. Improving Causal Assessment in Telecoupled Systems through Consistent Terminology

Although our literature review indicated that telecoupling studies generally discuss "causes" and "effects" in accurate ways, the complexity of telecoupling causality runs deeper than these concepts and is generally not acknowledged (or acknowledged inconsistently) in the predominantly descriptive studies published to date. Given this complexity and the overall scarcity of rigorous qualitative-quantitative causality assessments in the telecoupling literature, a standardized conceptual foundation for conducting these evaluations is needed. Here, we provide a terminology of telecoupling causality concepts (Table 3) to complement our prior description of best practices in telecoupling research and facilitate consistent, effective communication regarding telecoupling causality within and beyond the scientific community. This terminology is based on previous research in social science and land system science, with definitions for some cause-related terms modified from other sources to reflect unique attributes of the telecoupling framework. For instance, the definition of "cause" (a factor that influences the emergence and/or dynamics of a telecoupling; Table 3) is specific to the telecoupling framework despite its more general meaning as something that explains an effect. Moreover, it is important to note that our definition for "causal mechanism" (the process through which a cause produces its effect(s); adapted from [64,65]) is closely tied to context: the case-specific social-ecological circumstances influencing a causal mechanism (Table 3). It is critical for telecoupling researchers to evaluate context, as identical causes influenced by mechanisms operating in different contexts can produce dissimilar effects [65]. Robust, reliable understanding of causation in telecoupled systems and progress toward theory development can only be achieved by describing context and its interaction with causal mechanisms to produce effects [66]. This is particularly important because causal mechanisms can be linked in causal chains (i.e., sequences of causal mechanisms wherein particular effects serve as causes for subsequent effects [20], Table 3), making it imperative to evaluate relationships between proximate and ultimate causes of telecouplings using both qualitatively and quantitatively rigorous methods.

Table 3. Proposed definitions for terms related to causal attribution in telecoupling research.

Term	Proposed Definition	Related Citations
Factor	An event, fact, or variable that helps explain a telecoupling	Meyfroidt [20]
Cause	A factor that influences the emergence and/or dynamics of a telecoupling	Liu et al. [6]
Proximate cause	A factor that is a direct cause of the telecoupling under consideration	Meyfroidt [20]
Underlying (root) cause	An indirect cause of a telecoupling (i.e., causes a proximate cause)	Meyfroidt [20]
Effect	A consequence or impact of a telecoupling	Liu et al. [6]
Causal effect	A change in a response variable produced by change in an explanatory variable of a telecoupling	Meyfroidt [20]
Causal mechanism	The process through which a cause produces its effect(s) in a telecoupling	Falleti and Lynch [65], Meyfroidt [20]
Context	Case-specific social-ecological circumstances influencing a causal mechanism in a telecoupling	Falleti and Lynch [65]
Causal chain	A sequence of causal mechanisms wherein particular effects of a telecoupling serve as causes for subsequent effects	Meyfroidt [20]
Causal explanation	A description of the cause(s) of one or more effects of a telecoupling	Meyfroidt [20]

Interest in mechanismic research (i.e., studying how causes produce effects via mechanisms) has grown in recent years in the social sciences [36,64–68], mirroring nineteenth-century and early twentieth-century emphasis on mechanistic research (i.e., explaining physical phenomena using mechanical principles) in the natural sciences [69]. Although the term causal "mechanism" has at least nine distinct meanings [64], our use of the designation focusing on mechanisms as pathways/processes (see above and Table 3) reflects a common definition in contemporary social science [65,68] and provides a meaningful foundation for telecoupling research. By emphasizing mechanisms as pathways/processes, telecoupling researchers can focus their attention only on the critical details explaining causes and their effects; if supposed causal details have no influence on effects, they can be readily eschewed from further analysis [69]. Likewise, by facilitating the omission of unnecessary information about causes and effects, a mechanismic approach rooted in consistent terminology enables straightforward causal analyses that are harmonious within and among disciplines [64]. This conceptual unity would allow effective interdisciplinary communication and promote progress in scientific and applied arenas. Adopting a mechanismic approach for causal attribution is particularly important due to the inherent social-ecological integration of telecoupling research, wherein knowledge and experiences from multiple people and scientific fields must be synthesized in ways that foster meaningful applications for management and governance of telecoupled systems.

5. Opportunities and Challenges for Causal Analysis

Transforming telecoupling science into a causally rigorous discipline is an innovative research frontier with implications for improving how we understand and manage telecoupled systems. For instance, maximizing the accuracy and precision of telecoupling causal attribution will help optimize subsequent approaches for sustainable development and promote global initiatives such as the United Nations SDGs [31] and the Aichi Targets [32,34]. As demonstrated herein, rigorous qualitative-quantitative methods for telecoupling causal attribution (e.g., case studies combined with counterfactual analysis, statistical matching, synthetic controls, and process-tracing) are available [20] and need to be embraced by telecoupling researchers. Particularly close attention should be paid to causal effects and causal mechanisms, which serve as linchpins for socially and ecologically robust causal analysis. After all, it is necessary to understand causes and consequences, the processes connecting them, and the context underlying them to develop reliable, effective strategies for management and governance of telecoupled systems.

Despite these opportunities for telecoupling casual analysis, very few existing telecoupling studies include rigorous causal attribution. This overall scarcity likely reflects the challenges associated with applying specialized causal attribution methods that require extensive experience, interdisciplinary skill sets [35], and substantial resources (e.g., time, effort, money, personnel). Some of the systems for which the telecoupling framework has been applied are data-limited, or, even if data are available, they were collected with low sample sizes or over insufficiently long time frames. Increased collaboration among researchers from different disciplines and world regions would help address these issues. In addition, the spatial linkages and time lapses connecting causes and effects are not always consistent among telecoupled systems, causing variability in the difficulty of causal attribution. Moreover, telecoupling causes are often multidimensional: particular effects have multiple causes, each with unique mechanisms involving several (or more) proximate and underlying factors. Hence, there is a need to view telecoupling causal attribution through multiple disciplinary lenses. This represents both a challenge and an opportunity for causal analysis, as viewing casual attribution through multiple lenses is demanding yet ensures that researchers accurately and comprehensively evaluate causes, effects, and associated causal mechanisms.

To facilitate causal attribution through multiple lenses, we propose a typology of telecoupling causes based on six criteria: sector, system of origin, agent, distance, response time, and direction (i.e., producing positive or negative effects). Often, a given cause or causal chain fits multiple typological categories depending on the lens through which it is viewed, just as sending and receiving systems can be interchanged depending on the flow under consideration.

5.1. Sector-Based Causes

Causes can be categorized according to the sector (e.g., ecological, political, economic, humanitarian, technological, cultural) in which they originate. For example, introduction of Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) into the Laurentian Great Lakes in the mid-1960s was driven by socioeconomic, political, and ecological causes [70]. Millions of people within driving distance of the Great Lakes had more leisure time and expendable income (i.e., socioeconomic cause) than their predecessors, fostering demand for clean water and coastal recreational opportunities (e.g., fishing, beaches). Moreover, fisheries managers created salmon-focused recreational fisheries to supplement and replace commercial fisheries, which had become relatively defunct and politically weak (i.e., political cause) due to historical overfishing, invasive species, and habitat degradation (i.e., ecological causes; [70]). As another example of sector-based causes, the China Conservation and Research Center for the Giant Panda (*Ailuropoda melanoleuca*) has a panda loan program through which zoos inside and outside China can borrow pandas for one to several years. Sector-based causes of panda loans are cultural (i.e., affinity for this charismatic species), scientific (i.e., interest in panda research and conservation), technological (i.e., improvements in panda captive breeding and infant care), and economic (i.e., panda loans increase zoo visitation and revenue) [71–74].

5.2. Origin-Based Causes

Causes can also be classified according to the system (e.g., sending, receiving) in which they originate. In the case of Chinook salmon and coho salmon in the Great Lakes, eggs from these species were highly abundant in sending systems (e.g., fisheries agencies in Oregon, Washington, and Alaska), making it possible to send eggs from these states to Michigan in the mid-1960s [70]. Thus, sending system causes included high egg abundance, as well as social networks among fisheries professionals and agency regulatory structures that enabled egg transfer to Michigan. Causes in the receiving system (i.e., Michigan) included changing socioeconomic conditions (e.g., increased leisure time, expendable income), the decline of commercial fishing, and opportune ecological circumstances, as detailed above. In addition, causes have multiple system origins in transboundary telecoupled systems involving migratory species. For instance, sending, receiving, and spillover systems for migratory birds and bats often contain overwintering and breeding sites that face local social-ecological pressures (e.g., habitat loss) that cause population declines [15,53]. In particular, Kirtland´s Warblers (*Setophaga kirtlandii*) face threats (e.g., land conversion, nest parasitism by Brown-headed Cowbirds (*Molothrus ater*)) in sending, receiving, and spillover systems across their migration route from the Bahamas to northern Michigan, USA. However, telecouplings involving the spread of information about warbler conservation and habitat management from Michigan to other areas have promoted population recovery [75]. In the case of investments for intensive banana plantations in Laos, causes originated in a receiving system with a large demand for bananas (i.e., China) and a historical sending system that failed to fulfill that demand (i.e., Philippines; [63]). Overall, ascertaining the systems underlying telecoupling causes is important because causes often arise in more than one system, each of which can contain multiple causes.

5.3. Agent-Based Causes

Causes can also be classified according to the agents that provoke or promote them. For instance, recent growth in wood pellet trade has been promoted by the European Union through its Renewable Energy Directive and incentive programs as economical ways to convert biomass materials to fuel for meeting renewable energy goals [76]. Likewise, increased soybean production in South America is driven by multiple agent-based causes, including shifting diets among urban populations, trade barrier reductions implemented by governments, and improved transportation methods and logistics produced by engineers and traders [60,77]. Furthermore, the Chinese government was the main agent that caused large-scale rubber plantations to expand into the mountainous borderlands of northern Laos in the early 2000s. After the establishment of the Opium Replacement Program in 2004, the Chinese government provided financial and bureaucratic support to Chinese companies investing in rubber plantations in Laos, with the aim to replace opium plantations and curb opium trade [78].

5.4. Distance-Based Causes

Causes can also be differentiated based on physical distance (i.e., distant, adjacent, internal). In the case of Wolong Nature Reserve in China, tourism is the consequence of internal causes such as the strong desire for income, together with adjacent (intranational) and distant (international) motivations for wildlife and nature-based tourism [79]. Soybean area expansion in South America is mostly driven by distant causes (e.g., urban demand in China), but deforestation associated with the expansion of soybean cultivation is also linked to internal socioeconomic decisions and processes, including land speculation and cross-sectoral capital displacement [80]. Causes should also be distinguished based on social/psychological distance, as people that are physically distant can be socially/psychologically close, and vice versa.

5.5. Time-Based Causes

Causes can be classified according to the time lapse between their implementation or occurrence and their effect(s) on the emergence or dynamics of telecouplings. In the Peruvian anchoveta (*Engraulis ringens*) fishery, large, long-distance climatic systems such as the Pacific Decadal Oscillation affect ocean conditions and thus fish productivity over long time scales, whereas El Niño and La Niña events influence nutrient upwelling and fish production over shorter time scales [81]. The anchoveta stock collapse in 1972 resulted from causes that were relatively short-term (e.g., improvements in fish capture, processing, and storage technologies) and long-term (e.g., development of a political profit-seeking philosophy, diplomatic relations with distant fishing nations such as the Soviet Union). As another example, short-term causes of tourism include socioeconomic conditions in potential tourist destinations, yet over the long term, increases in tourism can cause negative environmental effects that may affect tourism rates [7]. In general, anthropogenic effects in telecoupled systems are produced by causes that operate over relatively short time scales, whereas system recovery—whether natural or policy-assisted—is often a slow process wherein causes operate over longer time spans.

5.6. Direction-Based Causes

Finally, causes can be differentiated according to the direction of their effect(s) (i.e., positive or negative). For instance, the creation and use of socioeconomic incentives and disincentives are "positive" causes that enhance habitat quality for migratory species conservation in response to the "negative" causes and effects of climate or land-use change [15,53]. "Positive" and "negative" causes are common in telecoupled systems involving tradeoffs. For instance, nature-based ecotourism is a "positive" cause of socioeconomic prosperity but often at the expense of increased pressure on natural systems [7], driven by causes operating in a "negative" direction. Conservation interventions in poverty-prone landscapes such as those in northeastern Madagascar are "positive" causes for the maintenance of biodiversity and ecological integrity of tropical forests, but they can be perceived by local land users as "negative" causes of reduced access to ancestral lands for the cultivation of subsistence and commercial crops [82].

5.7. Causes Can Have Multiple Typologies

Because causes often operate in combination (i.e., causal chains), it is important to classify telecoupling causes using multiple typologies. For instance, climatic systems in the Peruvian anchoveta fishery (e.g., Pacific Decadal Oscillation, El Niño and La Niña events) can be classified according to their sector (environmental), origin (sending, receiving, or spillover system), and agent (climate) [81]. They can also be categorized by distance and response time (long-distance and long-term for Pacific Decadal Oscillation, short-distance and short-term for El Niño and La Niña) and direction (El Niño and La Niña have negative and positive effects on anchoveta production, respectively). Ultimately, classifying telecoupling causes using multiple typologies allows for accurate, comprehensive causal attribution and thereby promotes more comprehensive identification of leverage points for change to improve the sustainability of telecoupled systems.

6. Conclusions

Rigorous qualitative-quantitative causal attribution is necessary for developing reliable strategies for sustainable management and governance of telecoupled systems. Herein, we provided an overview of causality in the telecoupling framework [6,7,13–16], a novel research approach that has been increasingly employed to understand and address major global sustainability challenges [34]. We found that current assessments of causality in telecoupling research have been mostly descriptive, due in part to the spatial and temporal complexities inherent in telecoupled systems. Hence, there is a pressing need and ample opportunity to embrace the wide range of rigorous, mixed qualitative-quantitative methods for studying causal effects and causal mechanisms.

To improve telecoupling research, we presented best practices for causal attribution (e.g., counterfactual analysis, process-tracing, root-cause analysis, comparative case studies) and developed a standardized casual terminology. We also suggested a typology of causes in telecoupled systems that provides a range of disciplinary lenses for causal assessment, leading to more rigorous and robust causal attribution. It is our hope that researchers will use approaches described herein to assess telecoupling causes, effects, and the mechanisms linking them, ultimately identifying leverage points for the sustainable management and governance of telecoupled systems.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/12/4426/s1. Figure S1: Flow diagram depicting the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) procedure as applied to a systematic review of telecoupling research from 2011 (earliest telecoupling publication) through May 2018, Table S1: Summary information for 89 peer-reviewed papers and book chapters related to telecoupling located via systematic review using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) procedure. Columns related to methods for assessing causal effects/mechanisms are phrased as questions with "Yes" or "No" answers (i.e., a particular publication did or did not employ the method in question).

Author Contributions: Conceptualization, R.D.G., A.K.C., J.G.Z., J.L.; Methodology, A.K.C., J.G.Z., P.R.F., R.F.B.S.; Validation, J.G.Z., A.K.C., P.R.F.; Formal Analysis, J.G.Z., A.K.C.; Investigation, A.K.C., J.G.Z., R.D.G., R.F.B.S., P.R.F., A.N.R.R., A.T., M.G.C., Y.L.; Data Curation, J.G.Z., A.K.C.; Writing—Original Draft Preparation, A.K.C., J.G.Z., R.F.B.S., P.R.F., A.N.R.R.; Writing—Review & Editing, A.K.C., J.G.Z., R.D.G., R.F.B.S., P.R.F., A.N.R.R., A.T., M.G.C., Y.L., J.L.; Visualization, J.G.Z., R.D.G., A.K.C.; Supervision, A.K.C.; Project Administration, A.K.C.; Funding Acquisition, J.L., A.K.C., J.G.Z., R.F.B.S.

Funding: A.K.C. was supported by the University Distinguished Fellowship and Robert C. Ball and Betty A. Ball Fisheries and Wildlife Fellowship [Michigan State University], the Conservation Scholarship Award [Fly Fishers International], and the United States Department of Agriculture National Institute of Food and Agriculture [grant number MICL04161]. J.G.Z. was supported by the Swiss Programme for Research on Global Issues for Development (r4d programme), which is funded by the Swiss National Science Foundation (SNSF) and the Swiss Agency for Development and Cooperation (SDC), under grant number 400440 152167. R.F.B.S. was supported by grants from Fundação de Amparo à Pesquisa do Estado de São Paulo (grant numbers 15/25892-7 and 14/50628-9). J.L. was supported by the U.S. National Science Foundation, NASA, Michigan State University, and Michigan AgBioResearch.

Acknowledgments: We thank presenters in the symposium "Telecoupling for Sustainable Development and Conservation Across Local to Global Scales" at the 2018 meeting of the U.S. Regional Association of the International Association for Landscape Ecology (US-IALE) in Chicago, Illinois for telecoupling discussions that demonstrated a need for this manuscript. We also thank symposium organizers and attendees for facilitating a productive environment for telecoupling discussions. We thank W.W. Taylor (Michigan State University) for helpful insights about the local-to-global connections among telecoupled systems described herein.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Krausmann, F.; Erb, K.H.; Gingrich, S.; Haberl, H.; Bondeau, A.; Gaube, V.; Lauk, C.; Plutzar, C.; Searchinger, T.D. Global human appropriation of net primary production doubled in the 20th century. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 10324–10329. [CrossRef] [PubMed]
2. Österblom, H.; Folke, C. Globalization, marine regime shifts and the Soviet Union. *Philos. Trans. R. Soc. B* **2015**, *370*. [CrossRef]

3. Liu, J.; Dietz, T.; Carpenter, S.R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A.N.; Deadman, P.; Kratz, T.; Lubchenco, J.; et al. Complexity of coupled human and natural systems. *Science* **2007**, *317*, 1513–1516. [CrossRef] [PubMed]
4. Kramer, D.B.; Hartter, J.; Boag, A.E.; Jain, M.; Stevens, K.; Nicholas, K.A.; McConnell, W.J.; Liu, J. Top 40 questions in coupled human and natural systems (CHANS) research. *Ecol. Soc.* **2017**, *22*. [CrossRef]
5. Tonini, F.; Liu, J. Telecoupling Toolbox: Spatially explicit tools for studying telecoupled human and natural systems. *Ecol. Soc.* **2017**, *22*. [CrossRef]
6. Liu, J.; Hull, V.; Batistella, M.; DeFries, R.; Dietz, T.; Fu, F.; Hertel, T.W.; Izaurralde, R.C.; Lambin, E.F.; Li, S.; et al. Framing sustainability in a telecoupled world. *Ecol. Soc.* **2013**, *18*. [CrossRef]
7. Liu, J.; Hull, V.; Luo, J.; Yang, W.; Liu, W.; Viña, A.; Vogt, C.; Xu, Z.; Yang, H.; Zhang, J.; et al. Multiple telecouplings and their complex interrelationships. *Ecol. Soc.* **2015**, *20*. [CrossRef]
8. Liu, J. Integration across a metacoupled world. *Ecol. Soc.* **2017**, *22*. [CrossRef]
9. Liu, J. Forest sustainability in china and implications for a telecoupled world. *Asia Pac. Policy Stud.* **2014**, *1*, 230–250. [CrossRef]
10. Wang, F.; Liu, J. Conservation planning beyond giant pandas: The need for an innovative telecoupling framework. *Sci. China Life Sci.* **2017**, *60*, 551–554. [CrossRef] [PubMed]
11. Gasparri, N.I.; Kuemmerle, T.; Meyfroidt, P.; le Polain de Waroux, Y.; Kreft, H. The emerging soybean production frontier in southern Africa: Conservation challenges and the role of south-south telecouplings. *Cons. Lett.* **2016**, *9*, 21–31. [CrossRef]
12. López-Hoffman, L.; Chester, C.C.; Semmens, D.J.; Thogmartin, W.E.; Sofia Rodríguez-McGoffin, M.; Merideth, R.; Diffendorfer, J.E. Ecosystem services from transboundary migratory species: Implications for conservation governance. *Annu. Rev. Environ. Resour.* **2017**, *42*, 509–539. [CrossRef]
13. Carlson, A.K.; Taylor, W.W.; Liu, J.; Orlic, I. The telecoupling framework: An integrative tool for enhancing fisheries management. *Fisheries* **2017**, *42*, 395–397. [CrossRef]
14. Carlson, A.K.; Taylor, W.W.; Liu, J.; Orlic, I. Peruvian anchoveta as a telecoupled fisheries system. *Ecol. Soc.* **2017**, *23*. [CrossRef]
15. Hulina, J.; Bocetti, C.; Campa III, H.; Hull, V.; Yang, W.; Liu, J. Telecoupling framework for research on migratory species in the Anthropocene. *Elem. Sci. Anth.* **2017**, *5*, 5. [CrossRef]
16. Deines, J.M.; Liu, X.; Liu, J. Telecoupling in urban water systems: An examination of Beijing's imported water supply. *Water Int.* **2016**, *41*, 251–270. [CrossRef]
17. Liu, J.; Yang, W.; Li, S. Framing ecosystem services in the telecoupled Anthropocene. *Front. Ecol. Environ.* **2016**, *14*, 27–36. [CrossRef]
18. Fang, C.; Ren, Y. Analysis of energy-based metabolic efficiency and environmental pressure on the local coupling and telecoupling between urbanization and the eco-environment in the Beijing-Tianjin-Hebei urban agglomeration. *Sci. China Earth Sci.* **2017**, *60*, 1083–1097. [CrossRef]
19. Liu, J.; Hull, V.; Moran, E.; Nagendra, H.; Swaffield, S.R.; Turner, B.L. Applications of the telecoupling framework to land-change science. In *Rethinking Global Land Use in an Urban Era*; Seto, K., Reenberg, A., Eds.; MIT Press: Cambridge, MA, USA, 2014; pp. 119–140, ISBN 9780262026901.
20. Meyfroidt, P. Approaches and terminology for causal analysis in land systems science. *J. Land Use Sci.* **2016**, *11*, 501–522. [CrossRef]
21. Lazarsfeld, P.F. Latent structure analysis. In *Psychology: A Study of a Science*; Koch, S., Ed.; McGraw-Hill: New York, NY, USA, 1959; Volume 3, pp. 476–543.
22. Elster, J. *Explaining Technical Change: A Case Study in the Philosophy of Science*; Cambridge University Press: New York, NY, USA, 1998; ISBN 9780521270724.
23. Mackie, J.L. Causes and conditions. *Am. Philos. Q.* **1965**, *2*, 245–264.
24. George, A.L.; Bennett, A. *Case Studies and Theory Development in the Social Sciences*; The MIT Press: Cambridge, MA, USA, 2005; ISBN 9780262072571.
25. Rudel, T.; Coomes, O.T.; Moran, E.; Achard, F.; Angelsen, A.; Xu, J.; Lambin, E. Forest transitions: Towards a global understanding of land use change. *Glob. Environ. Chang.* **2005**, *15*, 23–31. [CrossRef]
26. Lambin, E.F.; Meyfroidt, P. Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Pol.* **2010**, *27*, 108–118. [CrossRef]
27. Meyfroidt, P.; Lambin, E.F. Global forest transition: Prospects for an end to deforestation. *Annu. Rev. Environ. Resour.* **2011**, *36*, 343–371. [CrossRef]

28. Silva, R.F.B.; Batistella, M.; Moran, E. Drivers of land change: Human-environment interactions and the Atlantic forest transition in the Paraíba Valley, Brazil. *Land Use Pol.* **2016**, *58*, 133–144. [CrossRef]
29. Biesbroek, R.; Dupuis, J.; Wellstead, A. Explaining through causal mechanisms: Resilience and governance of social-ecological systems. *Curr. Opin. Environ. Sustain.* **2017**, *28*, 64–70. [CrossRef]
30. Greene, J.C.; Caracelli, V.J.; Graham, W.F. Toward a conceptual framework for mixed-method evaluation designs. *Educ. Eval. Policy An.* **1989**, *11*, 255–274. [CrossRef]
31. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015; Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld (accessed on 19 September 2018).
32. Convention on Biological Diversity (C.B.D.). In *The Strategic Plan for Biodiversity 2011–2020 and the Aichi Biodiversity Targets*; Secretariat of the C.B.D.: Montreal, QC, Canada, 2010.
33. United Nations Framework Convention on Climate Change. In *Adoption of the Paris Agreement. I: Proposal by the President (Draft Decision)*; United Nations: Geneva, Switzerland, 2015; Available online: https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf (accessed on 19 September 2018).
34. Liu, J.; Dou, Y.; Batistella, M.; Challies, E.; Connor, T.; Friis, C.; Millington, J.D.A.; Parish, E.; Romulo, C.L.; Silva, R.F.B. Spillover systems in a telecoupled Anthropocene: Typology, methods, and governance for global sustainability. *Curr. Opin. Environ. Sustain.* **2018**, *33*, 58–69. [CrossRef]
35. Ferraro, P.J.; Sanchirico, J.N.; Smith, M.D. Causal inference in coupled human and natural systems. *Proc. Natl. Acad. Sci. USA* **2018**. [CrossRef] [PubMed]
36. Biesbroek, R.; Termeer, C.J.A.M.; Klostermann, J.E.M.; Kabat, P. Rethinking barriers to adaptation: Mechanism-based explanation of impasses in the governance of an innovative adaptation measure. *Glob. Environ. Chang.* **2014**, *26*, 108–118. [CrossRef]
37. Passeron, J.C. *Le Raisonnement Sociologique. L'espace Non-Popperien du Raisonnement Naturel*; Nathan: Paris, France, 1991.
38. Gerring, J. The mechanismic worldview: Thinking inside the box. *Br. J. Polit. Sci.* **2008**, *38*, 161–179. [CrossRef]
39. Schiff, A.; Wright, L.; Denne, T. Ex-post evaluation of transport interventions using causal inference methods. In *NZ Transport Agency Research Report 630*; NZ Transport Agency: Wellington, New Zealand, 2017; 154p.
40. Ferraro, P.J.; Hanauer, M.M. Advances in measuring the environmental and social impacts of environmental programs. *Annu. Rev. Environ. Resour.* **2014**, *39*, 495–517. [CrossRef]
41. Winship, C.; Morgan, S.L. The estimation of causal effects from observational data. *Annu. Rev. Sociol.* **1999**, *25*, 659–706. [CrossRef]
42. Blackman, A. Evaluating forest conservation policies in developing countries using remote sensing data: An introduction and practical guide. *For. Pol. Econ.* **2013**, *34*, 1–16. [CrossRef]
43. Ferraro, P.J. Counterfactual thinking and impact evaluation in environmental policy. *New Dir. Eval.* **2009**, *2009*, 75–84. [CrossRef]
44. Rueda, X.; Lambin, E.F. Responding to globalization: Impacts of certification on Colombian small-scale coffee growers. *Ecol. Soc.* **2013**, *18*. [CrossRef]
45. Blackwell, M.; Glynn, A.N. How to make causal inferences with time-series cross-sectional data under selection observables. *Am. Polit. Sci. Rev.* **2018**. [CrossRef]
46. Jones, K.W.; Lewis, D.J. Estimating the counterfactual impact of conservation programs on land cover outcomes: The role of matching and panel regression techniques. *PLoS ONE* **2015**, *10*, e0141380. [CrossRef] [PubMed]
47. Elster, J. *Explaining Social Behavior: More Nuts and Bolts for the Social Sciences*; Cambridge University Press: New York, NY, USA, 2007; ISBN 9780521777445.
48. Runhardt, R.W. Evidence for causal mechanisms in social science: Recommendations from Woodward's manipulability theory of causation. *Philos. Sci.* **2015**, *82*, 1296–1307. [CrossRef]
49. Lambin, E.F.; Geist, H.J.; Lepers, E. Dynamics of land-use and land-cover change in tropical regions. *Annu. Rev. Environ. Resour.* **2003**, *28*, 205–241. [CrossRef]
50. Wu, A.W.; Lipshutz, A.K.M.; Pronovost, P.J. Effectiveness and efficiency of root cause analysis in medicine. *J. Amer. Med. Assoc.* **2008**, *299*, 685–687. [CrossRef] [PubMed]

51. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Med.* **2009**, *6*, e1000097. [CrossRef] [PubMed]
52. Schaffartzik, A.; Haberl, H.; Kastner, T.; Wiedenhofer, D.; Eisenmenger, N.; Erb, K.H. Trading land: A review of approaches to accounting for upstream land requirements of traded products. *J. Ind. Ecol.* **2015**, *19*, 703–714. [CrossRef] [PubMed]
53. López-Hoffman, L.; Diffendorfer, J.; Wiederholt, R.; Bagstad, K.J.; Thogmartin, W.E.; McCracken, G.; Medellin, R.L.; Russel, A.; Semmens, D.J. Operationalizing the telecoupling framework for migratory species using the spatial subsidies approach to examine ecosystem services provided by Mexican free-tailed bats. *Ecol. Soc.* **2017**, *22*. [CrossRef]
54. Tapia-Lewin, S.; Vergara, K.; De La Barra, C.; Godoy, N.; Castilla, J.C.; Gelcich, S. Distal impacts of aquarium trade: Exploring the emerging sandhopper (*Orchestoidea tuberculata*) artisanal shore gathering fishery in Chile. *Ambio* **2017**, *46*, 706–716. [CrossRef] [PubMed]
55. Leisz, S.J.; Rounds, E.; An, N.T.; Yen, N.T.B.; Bang, T.N.; Douangphachanh, S.; Ninchaleune, B. Telecouplings in East-West economic corridor within borders and across. *Remote. Sens.* **2016**, *8*, 1012. [CrossRef]
56. Silva, R.F.B.; Batistella, M.; Dou, Y.; Moran, E.; Torres, S.M.; Liu, J. The Sino-Brazilian telecoupled soybean system and cascading effects for the exporting country. *Land* **2017**, *6*, 53. [CrossRef]
57. Prell, C.; Sun, L.; Feng, K.; He, J.; Hubacek, K. Uncovering the spatially distant feedback loops of global trade: A network and input-output approach. *Sci. Total. Environ.* **2017**, *586*, 401–408. [CrossRef] [PubMed]
58. Sun, J.; Tong, Y.; Liu, J. Telecoupled land-use changes in distant countries. *J. Integr. Agric.* **2017**, *16*, 368–376. [CrossRef]
59. Crona, B.I.; Van Holt, T.; Petersson, M.; Daw, T.M.; Buchary, E. Using social–ecological syndromes to understand impacts of international seafood trade on small-scale fisheries. *Glob. Environ. Chang.* **2015**, *35*, 162–175. [CrossRef]
60. Fang, C.; Zhou, C.; Gu, C.; Chen, L.; Li, S. A proposal for the theoretical analysis of the interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations. *J. Geogr. Sci.* **2017**, *27*, 1431–1449. [CrossRef]
61. Easter, T.S.; Killion, A.K.; Carter, N.H. Climate change, cattle, and the challenge of sustainability in a telecoupled system in Africa. *Ecol. Soc.* **2018**, *23*. [CrossRef]
62. Schierhorn, F.; Meyfroidt, P.; Kastner, T.; Kuemmerle, T.; Prishchepov, A.V.; Müller, D. The dynamics of beef trade between Brazil and Russia and their environmental implications. *Glob. Food Secur.* **2016**, *11*, 84–92. [CrossRef]
63. Friis, C.; Nielsen, J.O. Land-use change in a telecoupled world: The relevance and applicability of the telecoupling framework in the case of banana plantation expansion in Laos. *Ecol. Soc.* **2017**, *22*, 30. [CrossRef]
64. Gerring, J. *Case Study Research: Principles and Practices*; Cambridge University Press: New York, NY, USA, 2007; ISBN 9780521676564.
65. Falleti, T.G.; Lynch, J.F. Context and causal mechanisms in political analysis. *Comp. Polit. Stud.* **2009**, *42*, 1143–1166. [CrossRef]
66. Meyfroidt, P.; Chowdhury, R.R.; de Bremond, A.; Ellis, E.C.; Erb, K.-H.; Filatova, T.; Garrett, R.D.; Grove, J.M.; Heinimann, T.; Kuemmerle, T. Middle-range theories of land system change. *Glob. Environ. Chang.* **2018**, *53*, 52–67. [CrossRef]
67. Falleti, T.G.; Lynch, J.F. From process to mechanism: Varieties of disaggregation. *Qual. Sociol.* **2008**, *31*, 333–339. [CrossRef]
68. Hedström, P.; Ylikoski, P. Causal mechanisms in the social sciences. *Annu. Rev. Sociol.* **2010**, *36*, 49–67. [CrossRef]
69. Angeles, P.A. *Dictionary of Philosophy*; Harper & Row: New York, NY, USA, 1981.
70. Crawford, S.S. *Salmonine Introductions to the Laurentian Great Lakes: An Historical Review and Evaluation of Ecological Effects*; NRC Research Press: Ottawa, ON, Canada, 2001; Volume 132, ISBN 978-0-660-17639-0.
71. Ellis, S.; Pan, W.; Xie, Z.; Wildt, D. The giant panda as a social, biological, and conservation phenomenon. In *Giant Pandas: Biology, Veterinary Medicine, and Management*; Wildt, D.E., Zhang, A., Zhang, H., Janssen, D.L., Ellis, S., Eds.; Cambridge University Press: Cambridge, UK, 2006; pp. 1–16, ISBN 978-0-521-83295-3.

72. Wildt, D.; Lu, X.; Lam, M.; Zhang, Z.; Ellis, S. Partnerships and capacity building for securing giant pandas ex situ and in situ: How zoos are contributing to conservation. In *Giant Pandas: Biology, Veterinary Medicine, and Management*; Wildt, D.E., Zhang, A., Zhang, H., Janssen, D.L., Ellis, S., Eds.; Cambridge University Press: Cambridge, UK, 2006; pp. 520–539, ISBN 978-0-521-83295-3.
73. Zhang, Z.; Zhang, A.; Hou, R.; Wang, J.; Li, G.; Fei, L.; Wang, Q.; Loeffler, I.K.; Wildt, D.E.; Maple, T.L.; et al. Historical perspective of breeding giant pandas ex situ in China and high priorities for the future. In *Giant Pandas: Biology, Veterinary Medicine, and Management*; Wildt, D.E., Zhang, A., Zhang, H., Janssen, D.L., Ellis, S., Eds.; Cambridge University Press: Cambridge, UK, 2006; pp. 455–568, ISBN 978-0-521-83295-3.
74. Buckingham, K.C.; David, J.N.W.; Jepson, P. Environmental reviews and case studies: Diplomats and refugees: Panda diplomacy, soft "cuddly" power, and the new trajectory in panda conservation. *Environ. Pract.* **2013**, *15*, 262–270. [CrossRef]
75. U.S. Fish and Wildlife Service, U.S. Forest Service. *Kirtland's Warbler Tourism Survey Summary: 2004–2013*; U.S. Fish and Wildlife Service: Falls Church, Virginia, 2016.
76. Parish, E.; Herzberger, A.J.; Phifer, C.C.; Dale, V.H. Transatlantic wood pellet trade demonstrates telecoupled benefits. *Ecol. Soc.* **2018**, *23*, 28. [CrossRef]
77. Garrett, R.D.; Rueda, X.; Lambin, E.F. Globalization's unexpected impact on soybean production in South America: Linkages between preferences for non-genetically modified crops, eco-certifications, and land use. *Environ. Res. Lett.* **2013**, *8*, 044055. [CrossRef]
78. Lu, J.N. Tapping into rubber: China's Opium Replacement Program and rubber production in Laos. *J. Peasant. Stud.* **2017**, *44*, 726–747. [CrossRef]
79. Li, W.; Han, N. Ecotourism management in China's nature reserves. *Ambio* **2001**, *30*, 62–63. [CrossRef]
80. Richards, P.D.; Walker, R.T.; Arima, E.Y. Spatially complex land change: The Indirect effect of Brazil's agricultural sector on land use in Amazonia. *Glob. Environ. Chang.* **2014**, *29*, 1–9. [CrossRef] [PubMed]
81. Orlic, I. Innovation, leadership, and management of the Peruvian anchoveta fishery: Approaching sustainability. In *Sustainable Fisheries: Multi-Level Approaches to a Global Problem*; Taylor, W.W., Lynch, A.J., Schechter, M.G., Eds.; American Fisheries Society: Bethesda, MD, USA, 2011; pp. 145–183, ISBN 978-1-934874-21-9.
82. Zaehringer, J.G.; Schwilch, G.; Andriamihaja, O.R.; Ramamonjisoa, B.; Messerli, P. Remote sensing combined with social-ecological data: The importance of diverse land uses for ecosystem service provision in north-eastern Madagascar. *Ecosyst. Serv.* **2017**, *25*, 140–152. [CrossRef]